REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
		FINAL REPORT 1 Dec 93 - 30 Nov 96

4. TITLE AND SUBTITLE
Novel Composite Materials for Nonlinear Optics and Information Storage

5. FUNDING NUMBERS
61102F
2301/CS

6. AUTHOR(S)
Professor Lawandy

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Dept of Engineering and Physics
Brown University
Providence, RI 02912-9104

AFOSR-TR-97
0170

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR/NE
110 Duncan Avenue Suite B115
Bolling AFB DC 20332-8050

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-94-1-0013

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE: DISTRIBUTION UNLIMITED

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

The work sponsored under this award resulted in the discovery of several important physical phenomena and the nucleating ideas behind three new technologies. Of particular importance was the discovery of laser action in strongly scattering media, a material now known as LaserPaint. This discovery has created a new field in optics which has an impact on light localization physics and many optical devices. The use of the technology in photodynamic therapy wa awarded a Rolex Award in 1996.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	

Directorate of Physics and Electronics
Department of the Air Force
Air Force Office of Scientific Research (AFMC)
Bolling Air Force Base
Washington, DC 20332-6448

Final Report
AFOSR Grant No. F49620-94-1-0013

Novel Composite Materials for Nonlinear Optics and Information Storage

by

Principal Investigator:
Nabil M. Lawandy
Professor of Engineering and Physics
Brown University
Providence, RI 02912-9104

April 15, 1997

Summary of Accomplishments for the Grant Period 12/1/93 - 11/30/96

The work sponsored under this award resulted in the discovery of several important physical phenomena and the nucleating ideas behind three new technologies. Of particular importance was the discovery of laser action in strongly scattering media, a material now known as LaserPaint. This discovery has created a new field in optics which has an impact on light localization physics and many optical devices. The use of the technology in photodynamic therapy was awarded a Rolex Award in 1996.

In addition to this important discovery, the group showed how trapped photoexcited carriers in glasses could produce selective etching. This work led to the elucidation of the charge pattern responsible for glass SHG using atomic force microscopy. Use of the technique also resulted in the determination of the role of centers in this process. The method was also extended to produce binary optical elements using direct laser writing and complemented a third technology we developed which uses semiconductor doped glasses to directly fabricate surface features in glass.

In total, the group produced 36 publications, 24 conference presentations, and three patents based on this work. In addition, the grant support has made possible the research of four new Ph.D.'s over the past three years.

Publications (1994 - 1996)

1. Driscoll, T. J., and Lawandy, N. M., "Optically Encoded Second-Harmonic Generation in Bulk Silica-Based Glasses," *JOSA B* **11(2)**, 355 (1994).

2. Gomes, A. S. L., and Lawandy, N. M., "Efficient Stimulated Raman Scattering Externally Seeded by Molecular Spontaneous Emission," *Optics Letters* **19(6)**, 408 (1994).

3. Gomes, A. S. L., Balachandran, R. M., and Lawandy, N. M., "High Intensity Absorption Saturation in Photodarkened CdS_xSe_{1-x} Doped Glasses," *Journal of Luminescence* **60&61**, 640 (1994).

4. Driscoll, T. J., and Lawandy, N. M., "Optically Encoded Sum-Frequency Generation in Silica-Based Glass," *Optics Letters* **19(1)** 7 (1994).

5. Beadie, G., Sauvain, E., Gomes, A. S. L., and Lawandy, N. M., "Temperature Dependence of Carrier Dynamics in CdS_XSe_{1-X} Doped Glasses Studied by Two Color Picosecond Spectroscopy," *Journal of Luminescence* **60&61,** 731 (1994).

6. Kweon, Gyeong-il, and Lawandy, N. M., "Resonance Dipole-Dipole Interaction in Electromagnetically Confined Geometries," *Journal of Modern Optics* **41(2)**, 311 (1994).

7. Kweon, Gyeong-il, and Lawandy, N. M., "Pair Excitations in Solids," *Physical Review B* **49(7)**, 4445 (1994).

8. Lawandy, N. M., Balachandran, R. M., Gomes, A. S. L., and Sauvain, E., "Laser Action In Strongly Scattering Media," *Nature* **368**(6470), 436 (1994).

9. Bernardin, J. P., Gomes, A. S. L., and Lawandy, N. M., "Anisotropic Nonlinear Beam Propagation in Ruby," *Optics Communications* **109**, 163 (1994).

10. Cohen, Jayson, Lawandy, Nabil M., and Suuberg, Eric M., "Fullerene-Catalyzed Oxidation of Organic Solvents," *Energy & Fuels* **8**, 810 (1994).

11. Lawandy, N. M., "Paint-on Lasers Light Up the Way to New Technologies," *Photonics Spectra* **28**(7), 119 (1994).

12. Khurgin, J. B., Lee, S.-J., and Lawandy, N. M., "Dynamic Wannier-Stark Effect in Semiconductor Superlattices," *Applied Physics Letters* **65**(24), 1 (1994).

13. Lawandy, N. M. and Balachandran, R. M., "Random Laser?", *Nature* **373**(6511), 203 (1995).

14. Sauvain, E., Kyung, Jae H., and Lawandy, N. M., "Multiphoton Micrometer-Scale Photoetching in Silicate-Based Glasses," *Optics Letters* **20**(3), 243 (1995).

15. Beadie, G., Sauvain, E., Gomes, A. S. L., and Lawandy, N. M., "Temperature Dependence of Carrier Relaxation in Semiconductor Doped Glasses," *Physical Review B* **51**(4), 2180 (1995).

16. Li, Shaozhong, Khurgin, Jacob B., and Lawandy, N. M., "Optically-Induced Anderson Delocalization Transition in Disordered Systems," *Optics Communications* **115**, 466 (1995).

17. Beadie, G., Sauvain, E., and Lawandy, N. M., "Low Dimensional Dispersive Transport at Nanocrystal Interfaces," *Solid State Communications* **94**(9), 709 (1995).

18. Kweon, Gyeong-il, and Lawandy, N. M., "Quantum Electrodynamics in Photonic Crystals," *Optics Communications* **118**, 388 (1995).

19. Balachandran, R. M., and Lawandy, N. M., "Interface Reflection Effects in Photonic Paint," *Optics Letters* **20**(11), 1271 (1995).

20. Vartak, S. D., and Lawandy, N. M., "Breaking the Femtosecond Barrier: A Method for Generating Attosecond Pulses of Electrons and Photons," *Optics Communications* **120**, 184 (1995).

21. Beadie, G. M., and Lawandy, N. M., "Single-Step Laser Fabrication of Refractive Microlenses in Semiconductor-Doped Glasses," *Optics Letters* **20**(21), 2153 (1995).

22. Nageno, Y., Kyung, Jae H., and Lawandy, N. M., "Compositional Dependence of Optically Encoded Second Harmonic Generation in Pure Binary Lead-Silicate and Ternary Barium Borosilicate Glasses," *Optics Letters* **20**(21), 2180 (1995).

23. Kyung, Jae H., and Lawandy, N. M., "UV Light Induced Selective Etching in Borosilicate Glasses for Micropatterning," *Electronics Letters* **32**(5), 451 (1996).

24. Kyung, Jae H., and Lawandy, N. M., "Maskless Photoencoded Selective Etching for Glass-Based Microtechnology Applications," *Optics Letters* **21**(3), 174 (1996).

25. Kyung, Jae H., and Lawandy, N. M., "Direct Measurement of Photoinduced Charge Distribution Responsible for Second-Harmonic Generation in Glasses," *Optics Letters* **21**(3) 186 (1996).

26. Balachandran, R. M., Pacheco, D. P., and Lawandy, N. M., "Laser Action in Polymeric Gain Media Containing Scattering Particles," *Applied Optics* **35**(4), 640 (1996).

27. Martorell, Jordi, Balachandran, R. M., and Lawandy, N. M., "Radiative Coupling Between Photonic Paint Layers," *Optics Letters* **21**(4), 239 (1996).

28. Lawandy, N. M., and Kyung, Jae H., "Selective Etching Unravels Frequency Doubling in Glasses," *Laser Focus World* **32**(3), 131 (March 1996).

29. Kyung, Jae H., and Lawandy, N. M., "Direct Observation of the Effective $\chi^{(2)}$ Grating in Bulk Glasses Encoded for Second-Harmonic Generation," *Optics Letters* **21**(9), 632 (1996).

30. Balachandran, R. M., Perkins, A. E., and Lawandy, N. M., "Injection Locking of Photonic Paint," *Optics Letters* **21**(9), 650 (1996).

31. Balachandran, R. M., Pacheco, D. P., and Lawandy, N. M., "Photonics Textile Fibers," *Applied Optics* **35**(12), 1991 (1996).

32. Vartak, S. D., and Lawandy, N. M., "Optically Controlled Imaging Phase Mask Element," *Optics Letters*, **21**(15), 1198 (1996).

33. Balachandran, R. M., and Lawandy, N. M., "Understanding Bichromatic Emission from Scattering Gain Media," *Optics Letters* **21**(19), 1603 (1996).

34. de Oliveira, Paulo C., Perkins, Amy E., and Lawandy, Nabil M., "Coherent Backscattering from High Gain Scattering Media," *Optics Letters* **21**(20), 1685 (1996).

35. Kyung, Jae H., and Lawandy, N. M., "Photoimpulsive Dispersive Relaxation of the Effective $\chi^{(2)}$ in Binary Lead-Silicate Glasses," *Optics Letters* **21**(10), 707 (1996). And Errata: *Optics Letters* **21**(21), 1795 (1996).

36. Vartak, S. D., and Lawandy, N. M., "Nonlinear Christiansen Filter," *Optics Letters* **21**(23), 1885 (1996).

Conferences (1994 - 1996)

1. Li, Shaozhong, Khurgin, Jacob B., and Lawandy, N. M., "Optically Induced Anderson Delocalization Transition in Randomly Disordered Systems," Paper No. QWC48, International Quantum Electronics Conference, Anaheim, CA, May 8-13, 1994.

2. Vartak, S., and Lawandy, N. M., "Electron Acceleration by Optical Rectification: Breaking the Attosecond Barrier," Paper No. QThC4, International Quantum Electronics Conference, Anaheim, CA, May 8-13, 1994.

3. Balachandran, R. M., and Lawandy, N. M., "Laser Action in Strongly Scattering Media," Paper No. QFE1, International Quantum Electronics Conference, Anaheim, CA, May 8-13, 1994.

4. Vartak, Sameer, and Lawandy, N. M., "Generation of Attosecond Electron Pulses Using Optical Rectification," Paper No. QTuL4, International Quantum Electronics Conference, Anaheim, CA, May 8-13, 1994.

5. Kweon, G., and Lawandy, N. M., "Quantum Electrodynamics in Photonic Crystals," Paper No. QPD12, International Quantum Electronics Conference, Anaheim, CA, May 8-13, 1994.

6. Balachandran, R. M., Lawandy, N. M., and Pacheco, D. P., "Laser-Like Emission from Strongly-Scattering Films and Gels," Paper No. MB6, Optical Society of America Annual Meeting, Dallas, TX, October 2-7, 1994.

7. Kyung, Jae H., Sauvain, E., and Lawandy, N. M., "Micron-Scale Maskless Photoetching in Transparent Borosilicate Glasses," Paper No. MP2, Optical Society of America Annual Meeting, Dallas, TX, October 2-7, 1994.

8. Balachandran, R. M., and Lawandy, N. M., "Spatio-Temporal Studies in Strongly-Scattering Gain Media," Paper No. TuN1, Optical Society of America Annual Meeting, Dallas, TX, October 2-7, 1994.

9. Vartak, S. D., and Lawandy, N. M., "Enhancement of Spontaneous Decay Rates by Plasmon Increased Vacuum Field Coupling," Paper No. Th14, Optical Society of America Annual Meeting, Dallas, TX, October 2-7, 1994.

10. Beadie, G., Sauvain, E., and Lawandy, N. M., "Lower-Dimensional Dispersive Transport in Cd(S, Se) Nanocrystallite Doped Glasses," Paper No. FF3, Optical Society of America Annual Meeting, Dallas, TX, October 2-7, 1994.

11. Sauvain, E., Kyung, Jae H., and Lawandy, N. M., "Photoinduced Micron Scale Maskless Etching in Transparent Glasses," Paper No. PD2.4, IEEE-LEOS Annual Meeting, Boston, MA, October 31 - November 3, 1994.
12. Balachandran, R. M., Pacheco, D., and Lawandy, N. M., "Photonic Textile Fibers," Paper No. CTul47, CLEO '95, Baltimore, MD, May 21-26, 1995.

13. Beadie, G., Vartak, S. D., Kyung, Jae H., and Lawandy, N. M., "Microlenses and Microlens Arrays Fabricated by Laser Heating of Semiconductor-Doped Glasses," Paper No. CTuK6, CLEO '95, Baltimore, MD, May 21-26, 1995.

14. Lawandy, N. M., Kondon, N. H., Balachandran, R. M., and Pacheco, D. P., "Photonic Paint for Laser Ranging and Target Identification," Paper No. CWJ5, CLEO '95, Baltimore, MD, May 21-26, 1995.

15. Vartak, S. D., and Lawandy, N. M., "Attosecond-Duration Anti-Bunched Electrons and Squeezed Photons," Paper No. QME2, CLEO '95, Baltimore, MD, May 21-26, 1995.

16. Kyung, Jae H., Lawandy, N. M., and Sauvain, E., "Bichromatic Harmonic Optical-Field Effects in the Photoinduced Etching of Borosilicate Glasses," Paper No. QThA4, CLEO '95, Baltimore, MD, May 21-26, 1995.

17. Khurgin, J. B., Lee, S. J., and Lawandy, N. M., "Dynamic Wannier-Start Effect in Semiconductor Superlattices," Paper No. QThG26, CLEO '95, Baltimore, MD, May 21-26, 1995.

18. Balachandran, R. M., and Lawandy, N. M., "Theory of Photonic Paint," Paper No. QPD16, CLEO '95, Baltimore, MD, May 21-26, 1995.

19. Kyung, Jae H., and Lawandy, N. M., "Measurement of Photo-Induced Charge Distribution in Seeded Second Harmonic Generation by Charge-Selective Etching in Glasses," OSA Topical Meeting: Photosensitivity and Quadratic Nonlinearity in Glass Waveguides '95, Portland, OR, September 9-11, 1995.

20. Lawandy, Nabil M., and Fromer, Neil A., "Single-Step Laser Fabrication of Microlenses and Microlens Arrays for Photonics Applications," Society for Imaging Science and Technology (IS&T) 49th Annual Conference, Minneapolis, MN, May 19-24, 1996.

21. Lawandy, Nabil M., and Driscoll, Timothy J., "Laser Action in Scattering Gain Media for Lasing Pixel Applications," Society for Imaging Science and Technology (IS&T) 49th Annual Conference, Minneapolis, MN, May 19-24, 1996.

22. Lawandy, Nabil M., "Physics and Applications of Laser Action in Amplifying Disordered Media," 1996 Canadian Association of Physicists (CAP) Annual Congress, University of Ottawa, Ontario, Canada, June 16-19, 1996.

23. Lawandy, N. M., "Laser Fabrication of Microlenses," Paper No. I-00094, Optical Society of America Annual Meeting, Rochester, NY, October 20-25, 1996.

24. Lawandy, Nabil M., "Charge Distribution in Glasses Exposed to Intense Bichromatic Fields: Controlling Electronic Transport Properties with Light," IEEE Lasers and Electro-Optics Society Annual Meeting, LEOS '96, Boston, MA, November 18-21, 1996.

Ph.D. Students and Undergraduate Research

Gyeong-il Kweon	Molecular Interactions in Electromagnetically Structured Systems (1994)
Guy M. Beadie	Picosecond Measurements of Photogenerated Carrier Transport at Semiconductor Nanocrystal-Glass Interfaces and Microlens Fabrication in Semiconductor Doped Glasses (1995)
Rammohan Balachandran	Laser Action in Scattering Gain Media (1996)
Jae H. Kyung	Microscopic Processes for Second Harmonic Generation and Applications of Selective Etching Effect in Photo-Encoded Glasses (1996)